K. Nondestructive Evaluation Tools for Evaluation of Laser-Welded Metals

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Objectives

- Develop fast, accurate, robust, noncontact nondestructive evaluation (NDE) tools and methodologies to replace current manual destructive testing of laser-welded sheet and structures in zinc-coated and uncoated steel and aluminum.
- Demonstrate accuracy and repeatability of the technologies developed or applied.
- Eliminate the need for highly trained/experienced NDE evaluator.

Approach

- Phase 1: assess state-of-the-art technologies, down-select, performance test using fabricated welded coupons in steel; correlate NDE test results with validation test results; and select technology for Phase 2.
- Phase 2: specify and build a bench prototype from the selected NDE methodology, conduct further validation testing using production laser-welded coupons and production parts in steel and correlate NDE test results with validation test results. Compare destructive test result to NDE test results obtained on production parts.
- Undertake the study of laser-welded coupons in aluminum using an equivalent approach.

Accomplishments

Phase 1:

- Completed original equipment manufacturer (OEM) weld flaw characterization.
- Completed selection of target laser-weld application.

- Defined preliminary NDE system functional specifications.
- Completed initial assessment of NDE state-of-the-art technologies.
- Completed controlled testing of four selected NDE technologies using laboratory-fabricated roof ditch laser-weld coupons.
- Completed analysis of vendor test results.

Phase 2:

- Defined NDE system functional specifications based on roof ditch application and production plant input.
- Selected through-transmission acoustic technology that is suitable for the roof ditch application as well as other weld configurations.
- Evaluated technology using
  - — steel roof ditch samples fabricated on laser-weld production equipment that are complete,
  - — aluminum lap-weld sheet samples fabricated on laser-weld production equipment, and
  - — steel roof ditch production part coupons that are planned.
- Completed analysis test results for steel roof ditch samples and analyses of results for aluminum lap-weld samples and steel production part coupons are projected to be complete by close of CY 2003.
- Monitor prototype build to optimize for roof ditch application.
- Select strategic course of action for prototype implementation and plant trial.

Introduction

Laser welding has been widely accepted by the automotive industry as an industrial process. Uses range from welding of tailor-welded blanks, to transmission component, to airbag inflation modules. The use of lasers continues to increase with some manufacturers considering the use of lasers for welding of the "body in white."

While laser welding is accepted by the automotive industry, cost factors are an issue, particularly with respect to weld discontinuities. With the high speed and high volume of laser, welding coupled with the relatively small critical flaw size, finding these discontinuities can be time-consuming, difficult, and thus, expensive. If not detected before subsequent processing and/or assembly, they could cause failures during processing down line or while in use. For example, porosity in a laser-welded tailor blank can cause failure during a stamping operation, which in turn can damage dies and cause downtime for the press. To forestall this, laser welding must be accomplished with no detrimental weld discontinuities, and the process and product output must be monitored with a high degree of reliability.

A number of systems have been developed to monitor laser welding systems in real time. Generally, these systems examine the byproducts of the laser-to-metal interaction to infer the quality of the weld itself. These process monitoring methods may include examination of the frequency and intensity of the light that is given off, for example, and compare it to those parameters known to have produced an "acceptable" weld. Most of these monitoring systems use this "training" method as a basis for determining if acceptable welds or unacceptable welds were created by the laser weld process. As of this writing, such systems are being applied in the production environment to gage the process, not as a substitute for weld quality inspection or destructive testing.

The USAMP is exploring NDE tools for use on the weld itself upon completion of the weld process. Of specific interest was the identification of progressive and emerging technologies in NDE. As part of this effort, the AMD 303 project performed phased assessments of NDE technologies, progressively narrowing down the technologies best suited to the production application. From these assessments, specific technology recommendations were reviewed and a technology chosen with the goal being to have a NDE prototype ready for installation in a factory setting by the end of calendar year 2003.

Details of Phase 1 and 2

Phase 1

Phase 1 was the assessment of state-of-the-art technologies, down-selection, testing using fabricated welded coupons, correlation of NDE test results with validation test results, and technology selection. The NDE capability sought was conceptually defined in terms of its functionality, and the laser weld discontinuities that must be detected were characterized.

An initial assessment of NDE technologies from which four technologies were selected for further evaluation, was completed in July 2001. The NDE techniques included in this assessment are identified in Figure 1. Commercial off-the-shelf systems were included along with emerging NDE technologies.

Four technologies were selected for detailed evaluation using a scientifically designed and statistically controlled study. The goal was to determine NDE performance capability using laboratory-fabricated weld samples, simulating laser-welded roof ditch welds (see Figure 2). At this stage of our research, it was not expected that any of the four technologies would prove to be 100% capable. Rather, the goal was to determine which technology offered the best array of detection capabilities and potential for enhancement and configuration as a

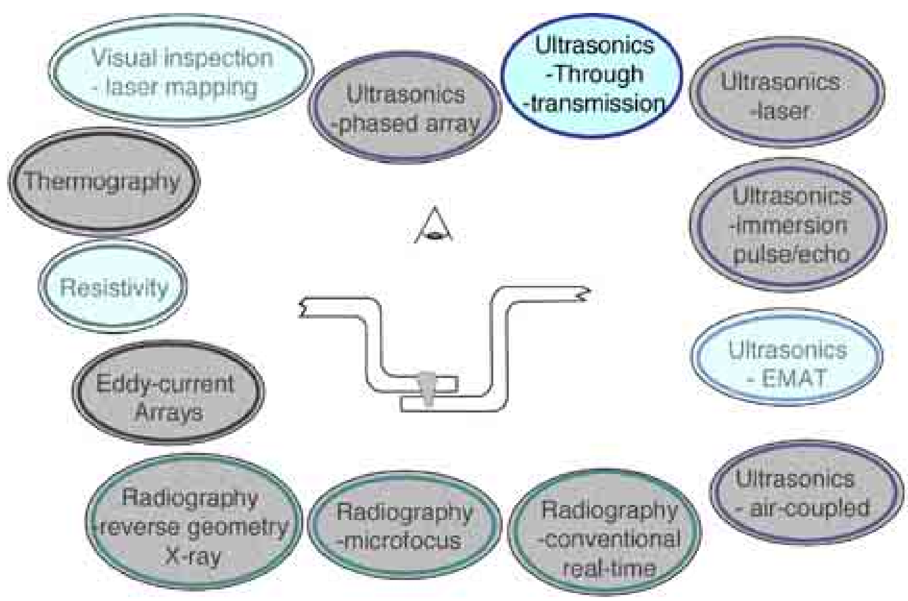

Figure 1. Phase 1 Technology assessment examining the capabilities of 13 technologies/techniques for their suitability to inspect the target weld configuration and the weld discontinuities of interest. Initial analyses identified four techniques, highlighted here, for detailed evaluation.

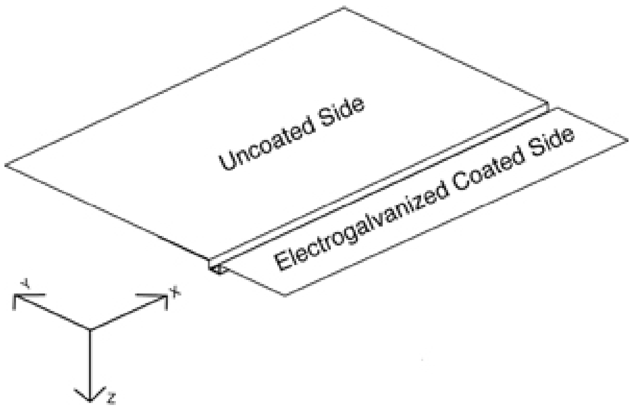

Figure 2. Overall dimensions of roof ditch weld sample: X = 400 mm; Y1 = 202 mm Y2 = 89 mm, overall Y after bending = 287 mm; Z = 12 mm.

prototype suitable for eventual testing in an automotive laser welding production application.

Validation of the laboratory-fabricated roof ditch weld samples in Phase 1 was done using microfocus and conventional radiography and, where appropriate, metallurgical evaluation rather than destructive tear down of the samples. Viewed as too valuable to destroy, the samples were preserved, thereby ensuring our ability to use them in future testing.

Following completion of these evaluations, the AMD 303 Committee undertook an extensive analysis of the data to arrive at an understanding of and consensus on a meaningful comparison of the results. All systems were found to have varying deficiencies:

- excessive false calls;
- missed discrepancies (off-location welds, porosity, lack of fusion);
- tendency to undersize the defects; and
- production suitability deficits.

Concluded in September 2002, this analysis resulted in down-selection to the two most promising technologies for further evaluation and possible prototype development in Phase 2.

Phase 2

The two technologies were found to differ in their capabilities for detecting certain weld discontinuities judged critical by the OEMs and a laser welding system provider. The two NDE systems, based on EMAT and ultrasonic technologies, performed comparably well (albeit on some differing discontinuities), and our conclusions indicated they required either additional development or reconfiguration to perform acceptably well in the OEM production environment. Ultimately, the ultrasonic technology was selected for Phase 2 in-depth evaluation, configuration, and build for the roof ditch weld application. See Figures 2 and 3 for roof ditch weld sample details.

Significant determinants in the decision to focus on the through-transmission ultrasonic technology were its

- demonstrated detection capabilities as they aligned with the production plant detection priorities (see Figure 4);
- demonstrated detection reliability, repeatability, and reproducibility during our testing regimes;
- ease of modification to incorporate additional capability using the pulse-echo ultrasonic technique;
- capability of being mounted on a robot arm or other automation;
- robustness of the device and its near-term prospects for commercialization;
- favorable detection cycle time compared to production cycle time;
- user interface friendliness and ease of training;
- motivation of the vendor to work with the automotive sector; and
- price feasibility for eventual plant purchasing.

Early in 2003, activities were directed at laying a sound statistical and experimental foundation for in-depth evaluations of the

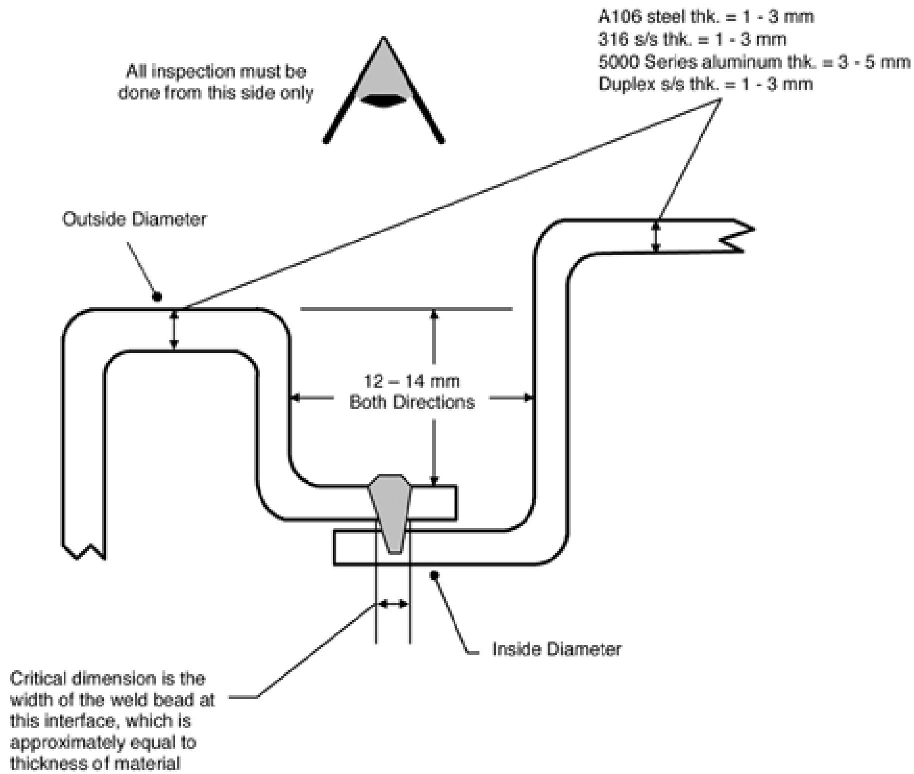

Figure 3. Laser-welded roof ditch joint details.

Discrepancy Detection Requirements

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Discrepancy Type	Detection Table			
	NDE-001 Defined	Plant Identified	Through-transmission Ultrasonics	Through-trans plus Pulse Echo
Lack of Fusion	?	?	?	?
Undersize Welds	?	?	?-	?
Underbead Cracks	?			?p*
Crater Cracks	?			?p
Longitudinal Cracks	?			?p
Transverse Cracks	?			?p
Missing Welds Skips	?	?	?	?
Pore, Porosity	?	?	?	?
Inclusions	?			?p
Burn-through & holes	?	?	?	?
Top Sheet Through-cut	?			?p
Undercut or Underfill	?			?p

*p means this detection capability may be possible with the addition of Pulse Echo capability to the UL2000.

Figure 4. Table comparing discrepancy detection requirements and through-transmission ultrasonic device capabilities with and without pulse-echo capability.

ultrasonic device. As part of this process, the AMD 303 team defined and executed:

- Engineering Specifications: NDE-001,
- NDE System Specifications, and
- Coupon Weld Specifications

The coupon test trials were conducted in strict adherence to a detailed test plan jointly defined by Ford, GM, and DaimlerChrysler NDE and statistics experts, in compliance with the specifications defined earlier. The test plan prescribes test regimes for

- calibration,
- RMS variation,
- baseline noise,
- gauge R&R, and
- surface roughness.

To test the device on coupons that are more closely aligned to the target production part than were the laboratory-built coupons in Phase 1, steel roof ditch coupons were fabricated using a production-equal welding cell in parallel with the OEM's laser-welding cell build program for the production plant. Steel roof ditch weld coupons containing known discrepancy sizes and two containing no discrepancies were created with a 4-kW Nd:YAG laser. Discrepancy types were limited to plant-defined priority types and discrepancy sizes ranged from 2.0 to 43.8 mm in length. In addition, lap-weld samples using 5000 series aluminum were fabricated in a production-equal laser welding cell that was configured for aluminum. These samples will be used in evaluating the performance of the through-transmission ultrasonic sensor on aluminum. The aluminum samples contain known defect lengths similar to steel coupons, and our preliminary tests would indicate that the signal obtained should be similar to that seen on the steel weld coupons.

Test trials were conducted on steel roof ditch coupons using a prototype through-transmission ultrasound sensor under the supervision of an independent auditor contracted by AMD 303 (Figure 5). As a result the project team can be assured that the testing regimes were followed as specified and can rely on the integrity of the resulting test data delivered to the team for analysis.

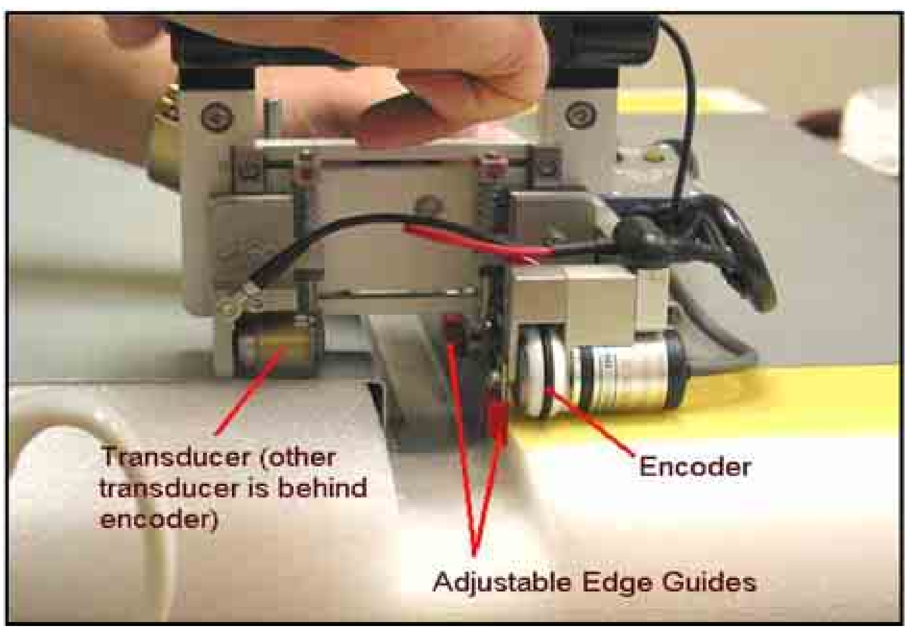

Figure 5. Through-transmission ultrasonic sensor prototype in test run over a steel roof ditch coupon.

Weld coupon validation testing was performed at GM on the steel and aluminum coupons using Immersion Ultrasonic pulse/echo "C-scans". C-scan results by sample are recorded on data sheets for every coupon/sample and later analyzed against the sensor's amplitude signature data outputs by sample upon completion of the testing. At the time of this report, analysis of the steel coupon testing results has been completed. Correlation of ultrasonic signature results with C-scan images can be graphically shown as done here in Figure 6.

Our analysis and findings for steel roof ditch coupons indicate that the through-transmission ultrasonic sensor has the following attributes:

- inspects 100% of weld (continuous),
- detects >99% of lack-of-fusion >8 mm,
- <1 in 10,000 of good welds called bad,
- scans at a speed of 600 mm/min (2 min/roof) at 1-mm resolution,
- monitors and provides feedback to operator if scanning speed is too fast,
- user friendly: red light/green light indicator,
- production-ready,
- can be automated, and
- system was tested with various operators, at various times, and proved to be user friendly and showed good reproducibility.

Testing of the ultrasonic sensor on the aluminum lap-weld samples and analysis of those results will be completed by calendar year end. Additionally, it is planned that production weld coupons will be cut from laser-welded roof ditch production parts and used to test the prototype being built for in-plant trials. Then, based on the analysis of its performance on the production part coupons, the through-transmission ultrasonic sensor will be placed in the target factory for plant tryout. Ultimately during tryout, the performance of the ultrasonic sensor will be correlated with production part tear-down data.

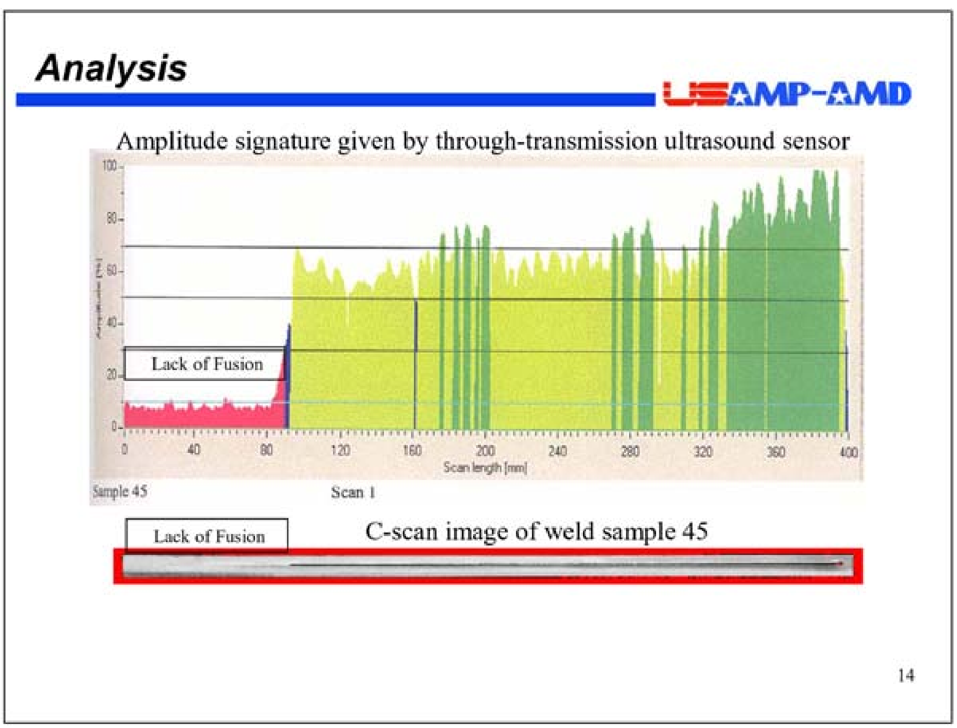

Figure 6. Correlation of the through-transmission ultrasound sensor results against the C-scan images with the area of weld discontinuity, lack of fusion, shown clearly in both images as annotated.